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A 5-KILOCYCLE LONG-RANGE SEARCH SONAR

[UNCLASSIFIED TITLE]

N. Shear, C. L. Buchanan, and J. B. Humphrey

Sonar Systems Branch
Sound Division

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NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

The further development of the long-range search program consisted of the design and construction of a 5-kc sonar system and its employment as a research tool in sonar studies. The transducer, a multielement array, was housed in a towed body. The towing and electronics systems vehicle is a converted LSM.

The studies showed that there are three necessary elements in sonar detection: the existence of an acoustic path, a sonar system to exploit the path, and a reliable vehicle to transport the sonar to the path. The importance of the limitations imposed by weather, sea state, and area accessibility upon the third factor have not been sufficiently stressed.

A major part of the research effort was expended in improving the towing system and in building up the body of knowledge required to design and build a workable and consistently reliable cable. The placement of conductors within the cable, with the small-gage, annealed conductors in the center, was found to be important in extending the electrical operating life of the cable.

The oceanographic and sonar detection data obtained are not inconsistent with prior hypotheses. Echo ranging in the absence of a surface duct was not improved by the lowered frequency.

PROBLEM STATUS

This is a final report on this problem, which has been closed as of April 4, 1958.

AUTHORIZATION

NRL Problem S05-12
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CHAPTER I

BASIC CONSIDERATIONS

BACKGROUND

In the past few decades, the balance between submarine and antisubmarine warfare has been uneasily maintained, and at the close of World War II the submarine appeared to have the upper hand. Advances in submarine performance already achieved by the Germans became known at that time. Subsequently, the potential effectiveness of long-range subsurface weapons was recognized. Because of these two developments and anticipated further improvements in both submarine and weapon, and in order to curb a recurrent surge of unbalance in favor of the submarine, attention was focused by 1948 on countermeasures, with emphasis on detection at long range. In line with this purpose, the long-range-search program was instituted at the U.S. Naval Research Laboratory. This is a continuing program at NRL for studying the long-range-search possibilities offered by active sonar.

Sound is propagated under water far better than any other form of energy; because of this fact, its application to long-range detection was studied by an ONR committee in 1948. A report prepared by that committee (1) showed a possibility of exploiting favorable acoustic paths when they exist to achieve substantial increases in detection range. In an effort to exploit this possibility to the fullest, the long-range-search program was instituted at NRL. In this program, the effectiveness of the sonar was to be enhanced by using low frequency, high power, a large transducer, and improved signal-processing devices. Conventional limitations of weight and space were to be bypassed (2).

The initial frequency used was chosen to be 10 kc, because this was the lowest frequency at which conventional transducer types could deliver high power. However, since at the start of the problem it was known that future research at 5 kc was being planned, research on 5-kc sonars was instituted. The first phase of the program was centered about a 10-kc equipment, designated LRS 1-10 (Ref. 3). The next phase of the program, the presently described one, is concentrated on a 5-kc gear, known as LRS 2-5. A program is underway for a 1-kc equipment, the LRS 3-1. In addition, considerable work has been done on a 2-kc dipped sonar for blimps and helicopters. Here the interesting interplay of elements in research come to the fore. Earliest analysis indicated some advantages to a 5-kc sonar (Fig. 1). Because of construction, design, and other practical considerations, the 5-kc research was deferred to the second step, and 10 kc was taken up first. However, during the LRS 1-10 phase, more specific information was obtained on acoustic losses in ducts. These new data gave rise to a different prediction of the advantages of 5 kc over 10 kc and made the 1-kc device appear even more desirable.

The assumptions or concepts upon which the program rested were twofold. To get long ranges, there must exist favorable acoustic paths, and the sonar must have low frequency and suitable equipment parameters to take advantage of the low frequency. To verify these assumptions, it was necessary to design and construct instrumentation in the form of sonar equipment as a research tool. This equipment was also needed for learning more about the ocean characteristics that affect sound propagation.

CONDUCT OF PROGRAM PRIOR TO 5-KC PHASE

The program objectives were approached by a three-step procedure. First, an analysis was made of the probable ranges which could be obtained with feasible equipments, disregarding conventional limitations of weight and space. The analysis was followed by a statement of the research problems to be studied with the projected equipment. Second, the feasibility of such an equipment was demonstrated by building an experimental sonar embodying the ideas of the above analysis. And third, further information about the factors which control echo ranges was obtained by means of the experimental system.

The LRS 1-10 obtained echoes from submarines at satisfactorily long ranges in surface-bounded ducts (Fig. 2, see Fig. 28 of Ref. 3). Reverberation did not limit echo ranges to the degree which was anticipated. In general, the results obtained with the 10-kc gear warranted proceeding to still lower frequency and experimenting with installations which incorporated lessons learned in the prior part of the program. During the LRS 2-5 phase, ideas heretofore not tested were to be tried out; the principal concern for feasibility was with the design and test of a 5-kc sonar and with the problems associated with towed sonar. On the research side, it was concerned with studying propagation at 5 kc and conducting further research into various sonar problems which the new equipment made experimentally possible.

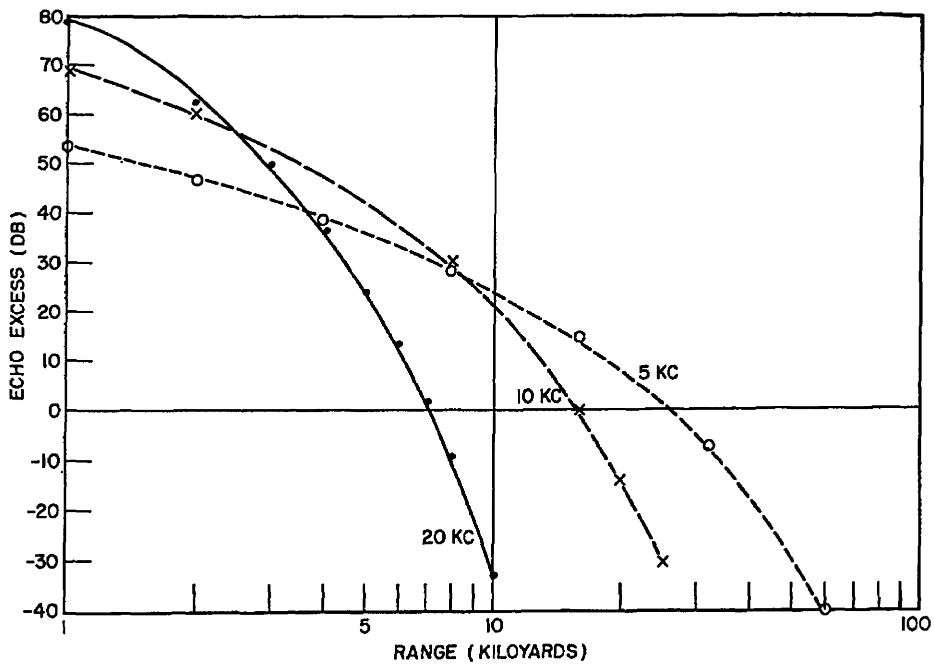

Fig. 1 - Dependence of echo excess and range on frequency. All parameters except frequency kept constant.

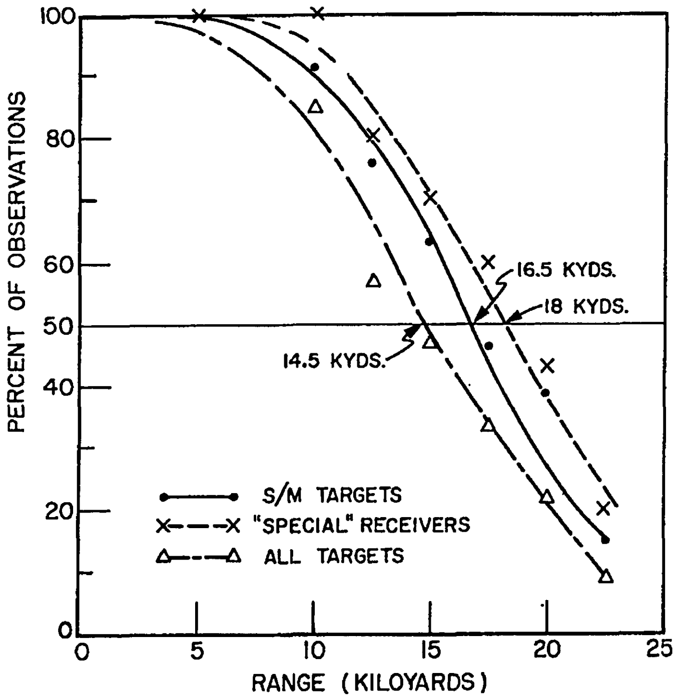

Fig. 2 - Detection capabilities of LRS 1-10

PRELIMINARY ANALYSIS

The preliminary analysis followed the same general pattern as the analysis presented in Ref. 3. The subjects considered were the lower frequency, acoustic paths, equipment characteristics, and range estimates. The estimated ranges are those to be obtained at 5 kc with the designed equipment employing the several acoustic paths. The details of this preliminary analysis are given in Appendix A.

5-KC PLANS

The program was planned to include studies of transmission over paths which were not successfully exploited in the LRS 1-10 program, namely, reflection via the bottom and propagation via the skip path. In surface-bounded ducts, information is desired on the relationship between the structure of the duct, the magnitude of the leakage coefficient, and the frequency dependence of the leakage coefficient. Reverberation was to be studied generally.

A different vehicle and platform were to be used in this phase of the program than in the LRS 1-10 phase. The sonar was to be towed from a landing-type surface ship.

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CHAPTER II

EQUIPMENT

INTRODUCTION

The previous chapter described the objectives of the long-range-search program, the accomplishments of the LRS 1-10, and the reasons for building the 5-kc system. In this chapter, the LRS 2-5 system will be described. Complete engineering details of the sonar system are given in a report devoted entirely to the LRS 2-5 equipment (4). The present report contains details only of parts of the system not described in Ref. 4

It appeared feasible to build a sonar with the following characteristics (Appendix A):

$$I = 136 \text{ db vs } 1\ \mu\text{bar}$$

$$\Delta = 24 \text{ db}$$

$$\delta = +18 \text{ db}$$

$$T = 20 \text{ db}$$

$$+N = -30 \text{ db vs } 1\ \mu\text{bar in a 1-cycle band}$$

This would give the system an echo excess E_1 (Appendix A), along the axis of the transducer at 1 yard from the face, of 192 db relative to 1 dyne/sq cm. The equipment part of the program is thus a project to design and build a system which satisfies the above E_1 and to learn how to handle it.

INNOVATIONS

In building a system with the characteristics listed above, several changes from the 10-kc gear were required. For many reasons, it was not sufficient merely to change the frequency and make a few minor alterations; a completely new design was required. The design which resulted in the LRS 2-5 equipment differed from that of the LRS 1-10 in the following components:

1. transducers
2. vehicle
3. handling methods
4. equipment layout
5. employment of rotating machinery as the transmitting power source.

The transducers of the LRS 2-5 gear were considerably larger than those of the LRS 1-10, which resulted in about equal directivity indices. In the LRS 1-10, the active elements were ADP crystals; in the LRS 2-5, they were either magnetostrictive nickel rings or lead-barium titanate ceramic tubes. The ADP crystal plates used in the 10-kc transducers were as large as the commercial growers supplied. It was not considered feasible or economical to grow larger ADP crystals for resonance at 5 kc, and so new element designs were required (5, 6).

In selecting ways of housing the transducer, it was necessary to take into account both the vehicle to carry the sonar and the methods of handling it aboard that vehicle. Considerations which favored towing the transducer from a surface ship were

1. size of the transducer

2. serious questions of servicing a large hull-mounted transducer with available drydocking facilities

3. the fact that successful experience had already been gained on submarine-installed gear, which suggested experimenting with an alternate type of vehicle.

The decision was made to employ a landing-type vessel as the vehicle and to build a center well through which the transducer and housing could be hoisted and towed.

With the assignment of the LSM as the vehicle, a towing system was developed. Originally a tandem-tow-cable assembly which consisted of a load-bearing wire rope and an electrical cable was used (7). This assembly was superseded by an electrical cable encased in a load-bearing steel-wire armor as a single assembly.

Another innovation was a complete duplication of the electrical installation, located on opposite sides of the ship. Because of this dual arrangement, a temporary installation could be made on one side without disturbing the balance, safety, or orderliness of the other. In addition, if some mishap rendered equipment inoperative on either side, an exact duplicate was immediately available. The high power capabilities of the transducers called for novel and more powerful energy sources for the drivers than had previously been employed. To attain this goal, two novel electrical rotating machinery systems were used; the 5-kc diesel driver (8) was developed for this system, and a motor-generator set used in conjunction with a conventional electronic driver, a system employed briefly in the LRS 1-10.

THE SYSTEM

The system consisted of elements which were described in detail in Ref. 4. These elements can be grouped into six classes.

1. exterior components

    a. Transducers
    b. Towed body
    c. Tilt-train mechanism
    d. Handling mechanism
    e. Cable

2. Transmission components

3. Reception components

    a. Receivers
    b. Displays

4. Program control

5. Research auxiliaries

    a. Monitors
    b. Data-recording system

6. Transient equipment

The system was installed on LSM-398.* Figure 3, taken from Ref. 7, shows the location of the center well, the transducer, and fish streaming. It also shows the location of the sonar spaces. Figure 4, taken from Ref. 4, is a block diagram of the system. Details of construction of all the units of the system are contained in the NRL Maintenance Manual for the 5-kc equipment.†

SPECIAL SIGNAL-PROCESSING DEVICES

A sonar signal-processing device used in this program but not described in Ref. 4 is known as the Narrow-Band Selective-Time-Delay System (NB-STDS) and was developed for operation with the LRS 2-5 equipment. The techniques employed in this system are similar to those used in the Selective Time-Delay System operated successfully at 10 kc (Ref. 9). The NB-STDS consists of a signal source which generates a train of equally spaced, frequency-coded pulses which are amplified and applied to the transducer to form a multiple-pulse ping, and a special receiver and display unit for processing the return from the ping.

The outgoing ping consists of eight 300-millisecond pulses, transmitted at the rate of one per second. Each pulse in the train is transmitted at a frequency 7 cps lower than the preceding one. Own-doppler compensation is applied to insure that the center of the desired frequency band is present in the water.

Returning signals and noise are amplified in a variable-gain amplifier controlled by a modified TVG function. This function could be manually adjusted to give an approximate fit to any of a variety of reverberation conditions. The signals are then applied to an array of contiguous narrow-band filters, each having a bandwidth of 7 cps. The outputs of the individual filters in the array are detected, and the resulting envelopes are displayed on adjacent channels of a special multipen chemical recorder. The pens are displaced along the time-base formed by the moving recorder paper so that echoes appeared as regular horizontal patterns in a random background.

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*The designation is now EAG-398.

†Since this sonar is entirely experimental and only one exists, the maintenance manual has not been distributed. However, if more interest exists for further particulars of the unit designs than given here, they may be obtained from this Laboratory.

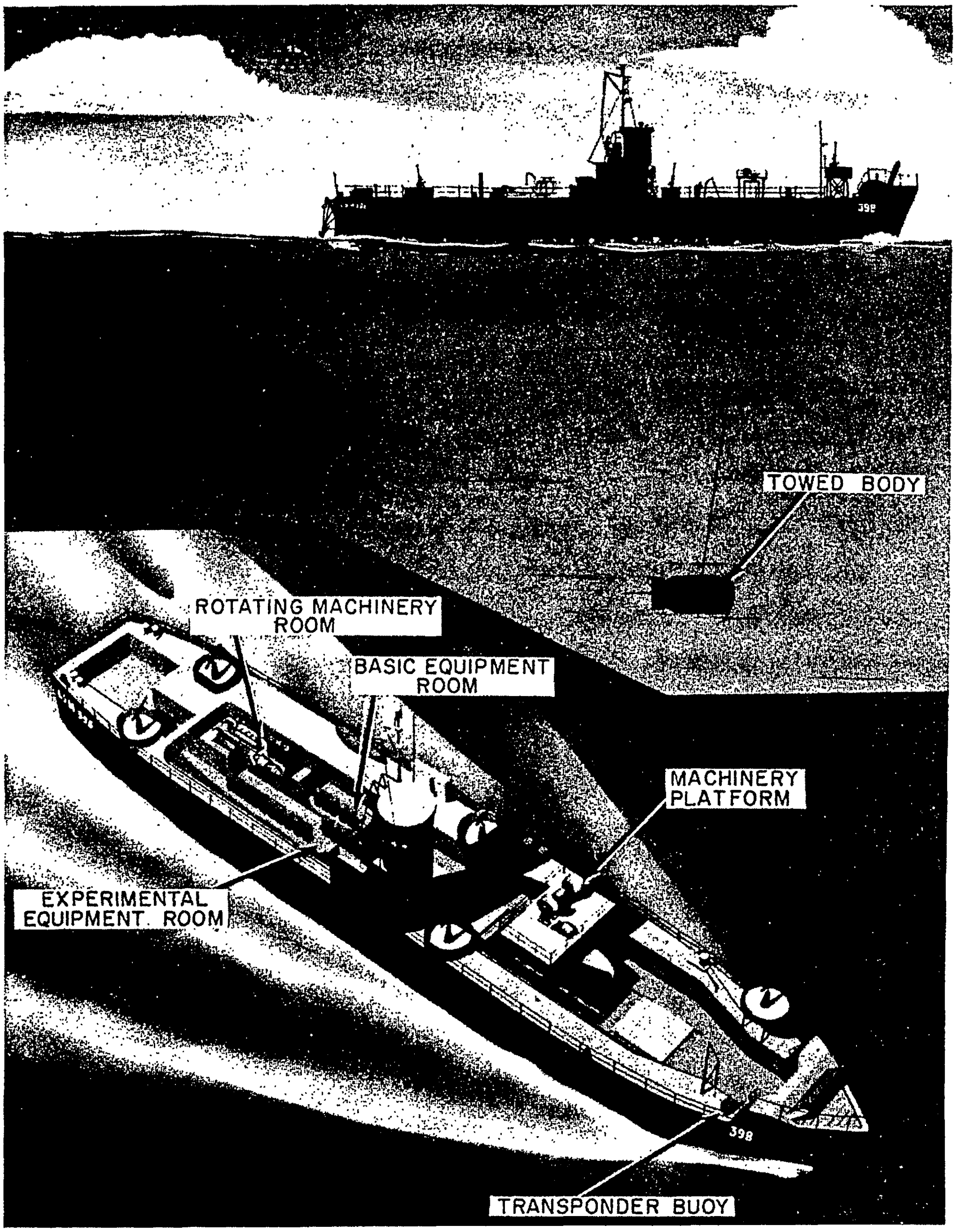

Fig. 3 - Drawing of LRS 2-5 system

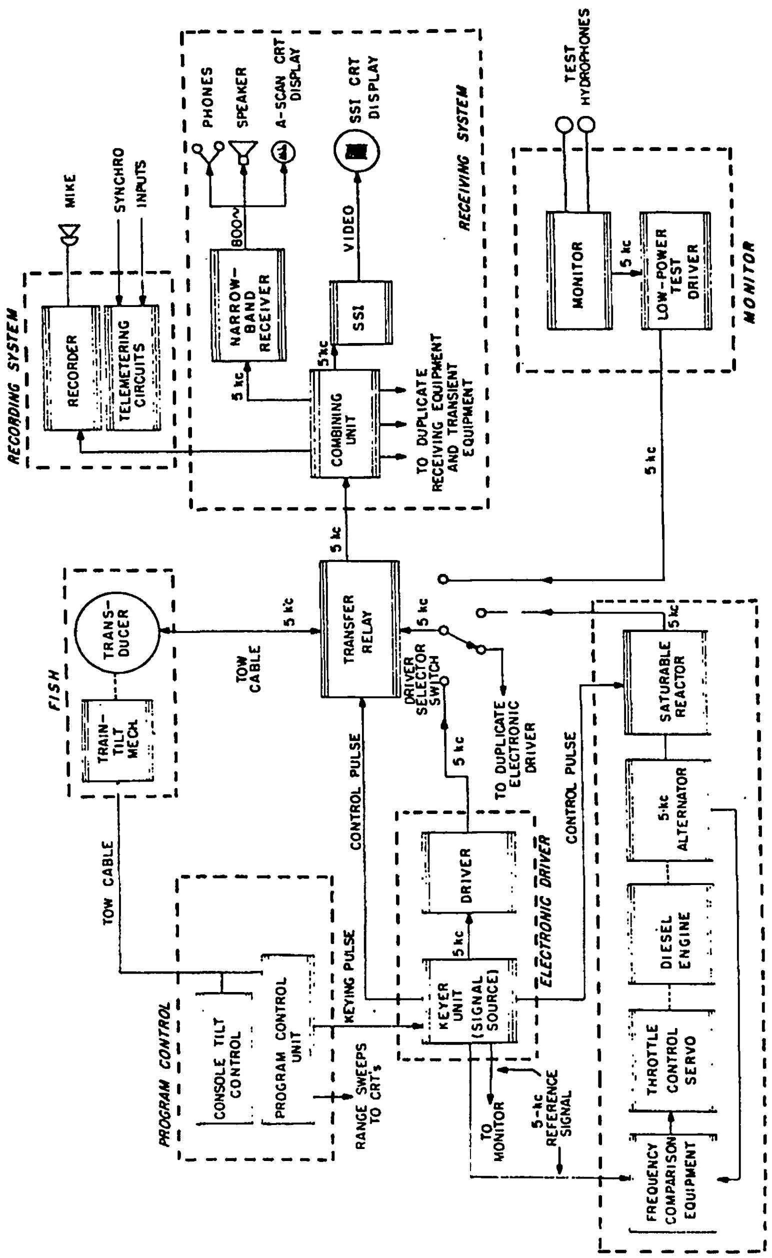

Fig. 4 - Block diagram of LRS 2-5 sonar system

The techniques employed in the NB-STDS include two significant departures from those employed in the earlier 10-kc device. The use of very narrow filters not only yields an improved signal-to-noise ratio by reducing the noise energy accepted in any given channel but also provides quantitative doppler information to aid in classifying and tracking submerged targets. The use of a new multifingered stylus in the display recorder greatly increases the number of just-noticeable differences which can be discriminated visually (10). Under optimum conditions, intensity differences of 0.5 db or less can be observed.

The NB-STDS was developed specifically for use with the LRS 2-5 sonar system. As such, it does not represent an operational device. To reduce the complexity of this experimental signal-processing equipment, only 12 filters were incorporated in the filter array. It was assumed that field operations would be conducted with controlled targets and that the approximate range rate would be known. Thus, using heterodyne techniques, the filter array could be adjusted on the basis of a priori information to permit "target-acquisition" studies with simple equipment regardless of range rate. Without such an arrangement, an array of more than 30 filters would be required, with attendent additional complexity of display techniques.

The sonar system, including the transducer, electronics, vehicle, and special devices, was thus devised. It became available for research in equipment design and, should that prove satisfactory, for research in acoustic oceanography.

* * *

CHAPTER III

OPERATIONS AND DATA

INTRODUCTION

The preceding chapters described the analysis which predicted that long detection ranges appeared attainable by active sonar and described briefly the success obtained with one model, the LRS 1-10. There followed a description of the equipment used in a second model, LRS 2-5. The present chapter describes the program of operations, the development of a cable suitable for the towing system, and the acoustic and oceanographic data which were obtained with the equipment.

The data obtained with the LRS 2-5 equipment were taken to provide additional information about the factors which control the detection ranges and to supplement the data obtained with the LRS 1-10 sonar. During the conduct of the tests, however, it was found that the sonar platform and vehicle were among the limiting factors in the system behavior and thus in the sonar performance. Therefore, a discussion of the platform is included, together with a description of the experimentation associated with it.

The data obtained are limited in number but are considered reliable. Even though data are few, they may be useful to other workers in the field for comparison with other observations.

PROGRAM OF OPERATIONS

Shipyard planning for the LRS 2-5 shipboard installation on the USS LSM-398 commenced in August 1953 at the Norfolk Naval Shipyard.

The ship's modification as contemplated required the installation of a well 30 ft long and 12 ft wide on the centerline, about 50 ft from the bow. Two well covers, to keep the opening normally closed, can be opened by rolling fore and/or aft on rails mounted on the main deck. A platform constructed above the well provided support for an electrical-cable winch and a towing winch to launch and retrieve the towed body. Compartmentation was provided by covering the main deck partially at the superstructure deck level and dividing the enclosed space with suitable bulkheads.

Trials at sea early in April 1954 revealed design deficiencies in the towed-body handling gear which would require rather extensive modification to provide the strength and torque required to control safely a 15-ton body at sea. Since plans for changes to structure and machinery were estimated to require about a month, the ship was brought to NRL for installation of as much of the electronics portion of the system as time would allow.

The ship returned to the Norfolk Yard around the middle of May. The design and shop work required were considerably greater than had been originally estimated, and the improved handling system was not ready for its second sea trials until August 16, 1954.

Table 1
Program of Operations

Dates 1955	Operating Hrs. Total	Operating Hrs. Submarine	Types of Operation	Targets	Area	Range (Kyd)
13 - 21 Feb	32	-	Shakedown	Of opportunity	Va. Capes	18
7 - 11 Mar	36	-	Equipment calibration - Beam Patterns - Noise measurements	-	Va. Capes	-
14 - 16 Mar	24	-	Ships machinery noise measurements	-	Va. Capes	-
4 - 7 Apr	41	-	Transponder calibration	-	Va. Capes	-
11 - 26 Apr	54	-	Sonar ranging - Bearing resolution	Transponders	Puerto Rico	32
14 - 16 June	21	-	Noise measurements - AT-258	-	Va. Capes	-
20 - 23 June	26	26	Propagation - Echo ranging	Submarine	Va. Capes	13
5 - 14 July	53	53	Echo ranging	USS GRAMPUS	Bermuda	21
2 - 4 Aug	28	28	Propagation - Resolution	USS BURFISH, Transponder	Va. Capes	4.5
20 - 22 Aug	22	-	SSI Resolution - Classification	Transponders, Reefs, Ridges	Off Georgia Coast	24
26 - 31 Aug	20	-	SSI Resolution - Classification	Of opportunity	Bahamas	24 ship 38 reef
22 Sep - 1 Oct	58	58	Echo ranging	USS SEA LION, Transponder	Bermuda	23 35
3 - 6 Oct	33	-	Propagation	Transponder	Va Capes	-
31 Oct - 8 Nov	32	-	Classification	Of opportunity, Bottom	S. Atlantic Coast	24
21 - 23 Nov	22	22	Echo ranging	USS REDFIN	Va. Capes	18
28 - 30 Nov	15	15	Special receiver	USS REDFIN	Va. Capes	5
TOTAL	517	202				

vibration-free, long-enduring lines are hard to come by, particularly when they are required to operate at ship speeds of 20 knots and above. The low maximum speed of the LSM, 12 knots, along with the weight of the towed body (20,000 pounds in water), made unimportant the low drag requirement. Drag, stability, and vibration of a towline can be controlled by a well-designed fairing, but with drag not a factor, it was decided to try the tandem towline, with which some measure of success was had when used with smaller sized equipments. The tandem line effectively controls stability and vibration, but its drag is approximately as great as that of a single round cable.

The development of the tandem line was instigated by the work done by DTMB (11), on rigid pipes in tandem, in an investigation relating to submarine periscope vibrations. The initial studies on such towlines by NRL is reported in Refs. 12 and 13. The tandem line used on the LSM-398 for the work on the LRS 2-5 sonar consisted of a leading line, standard 1-1/2-in.-diameter wire rope, followed by a rubber-covered electrical cable of the same diameter, separated one diameter by steel clips; the clips were spaced every two feet along the length of the cable. It appeared that the tandem towline would be an economical substitute for the faired towline, insofar as stability and vibration are concerned.

No success was had with the tandem towline in this program. It is believed that this was not due to a failure of the basic idea but rather to the way the towline was employed. Many difficulties were encountered; among them were crushing of the clips as the towline passed over the sheaves, the clip-unclip handling procedure (the electric cable and clip were reeled under slight tension on a separate drum from the wire rope, again to negate crushing loads on the clips), and fragility of the rubber-covered electric cable exposed to the mechanical hazards of reeling over sheaves and past rollers. With the experimental work in acoustics in a state of jeopardy because of these difficulties and the concomitant delays for repairs, a new towline was adopted. This substitute was a special electrical tow cable which consisted of a plastic-sheathed multiconductor cable (electrical portion) surrounded by two oppositely wound layers of galvanized improved plow-steel wires (strength portion), making a total diameter of about two inches. This cable has a calculated breaking strength of 235,000 pounds. The use of such a cable, which is allowed to stream through the water without any measures being taken to reduce either its drag or vibration, is permissible only because of the slow speed of the towing ship. The drag of the cable is small at low speeds when only 100 ft is paid out, and the weight of the cable and, more important, the weight of the towed body was sufficiently high to give a good towing configuration.

The special electric tow line was not a complete success at first try. The vibration of the cable under tow caused a mechanical breakage of many of the small electric conductors located toward the periphery; however, none of the larger coaxial conductors, located about the center, ever broke during cumulative periods of towing totalling several hundreds of hours. A redesign of the electric cable which provides for more flexible conductors and locates the smaller conductors toward the center of the cable is expected to eliminate the breakage when it is used on future sonar field tests.* Two other mechanical factors were introduced to minimize conductor breakage due to cable vibration. These were the precaution of changing towing depth a few feet every few hours to prevent excessive working of a discrete portion of the cable at the tow point, and the incorporation of a large-radius towing "horn." This horn was installed on the carriage, replacing the towing sheave. This horn is an assembly of four plates, each of a single plane of curvature sufficient to provide a bending radius of four feet for the cable in both the fore, aft, and athwartship directions. It eliminated the local high strains on the cable caused by the flanges of the towing sheave.

*This proved to be the case in subsequent experiments towing a 1-kc sonar.

PROPAGATION

A general discussion of propagation loss term is given in Ref. 3, together with its meaning and methods of measurement. The assumptions and analysis made in that report are again employed. Newly acquired data, subsequent to the publication of that report, do not change those previous assumptions.

Duct Transmission

In experiments on transmission through surface-bounded ducts, there were both echoes and one-way-transmission observations. In the one-way transmissions, the observed leakage was 1/2 db/kyd under the following conditions: sea state 1, duct thickness of 200 ft, transducer depth 50 ft, and surface temperature 78°F. The value of 1/2 db/kyd for leakage was arrived at in the following way. Data were taken from a short range of 1000 yd (one way) to 70,000 yd. A calibration level was established at range 1000 yd, and cylindrical spreading was assumed between 1 and 70 kyd; i.e., 10 log R between R = 1 and R = 70, where R = range in kyd. The total loss between 1 kyd and 70 kyd was measured as 62 db; of this loss, 18.5 db is due to spreading (10 log 70) and 7.7 db to absorption (14). The remaining loss, 35.8 db, is considered due to leakage out of the duct.

The numerical value for α_L (leakage coefficient) is somewhat lower than reported in Ref. 15. Figure 5, taken from that report, shows the summary of earlier work on this subject and is a plot of leakage coefficient as a function of frequency over the interval 1 to 5 kc. However, a value of 0.5 db/kyd checks closely with a formula presented in the SADD report (16).

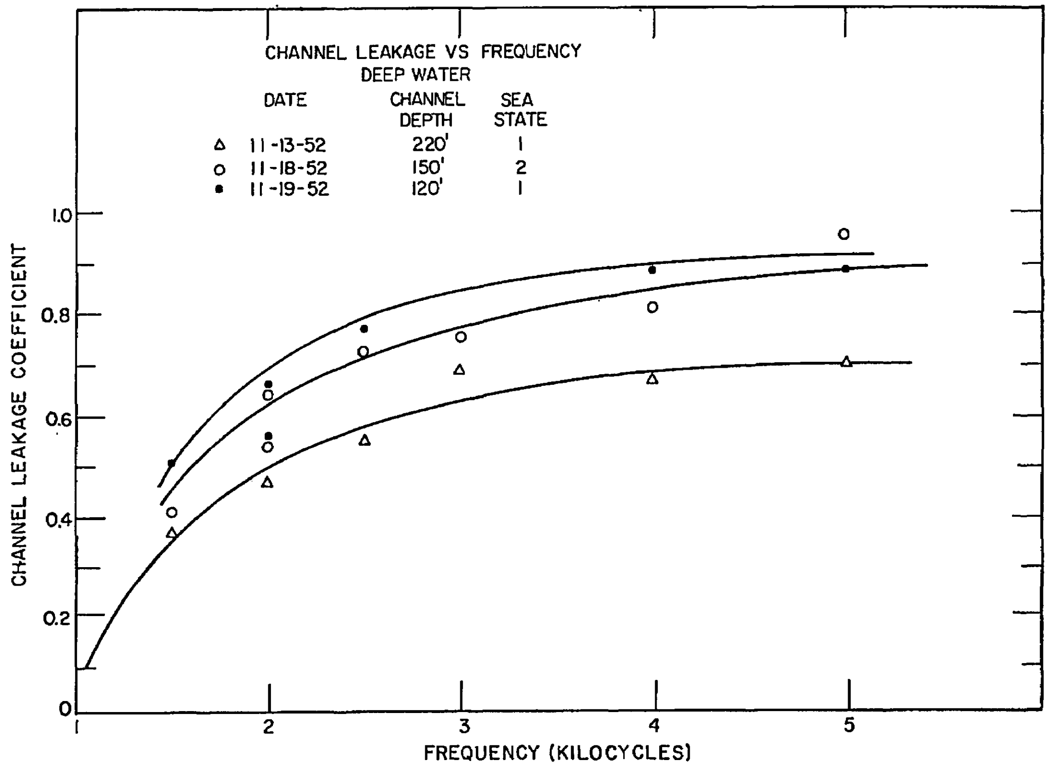

Fig. 5 - Channel leakage coefficient as a function of frequency

Bottom Reflections

In Ref. 16, measurements are presented which show that the sound reflected from the bottom had a beam pattern which was much broader than the beam pattern of the incident sound. Figure 6 (17) summarizes these data.

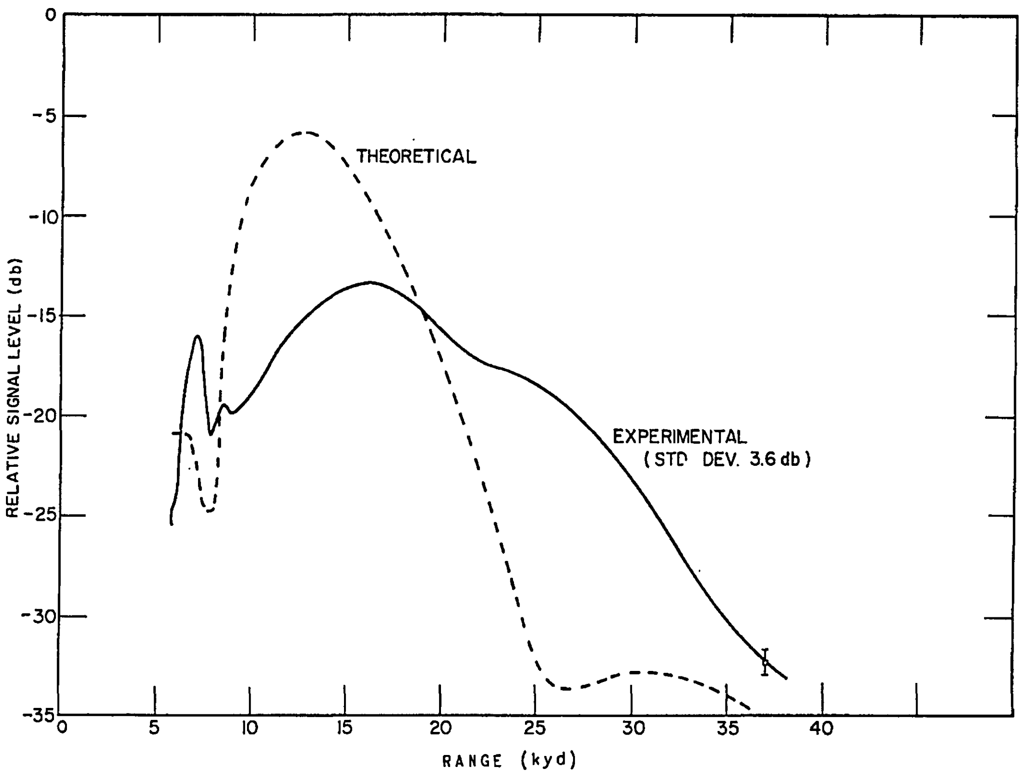

Fig. 6 - One-way propagation loss over a bottom-reflected path using a directional transmitter

On October 6, 1955, measurements were taken in 1500-fathom water off Norfolk at latitude 36°N and longitude 75°W, at a spot selected for its uniformity in depth. One-way propagation by way of the bottom-reflected path was measured using a 5-kc transducer (directivity index 24 db), tilted down 20 deg; the range was closed from 37 kyd to 6 kyd. In processing the data, the received level was first corrected for divergence and absorption losses and then scale plotted against range. The resulting response curve peaked at about 16 kyd, although it was expected from the geometry to peak at 13 kyd.

In Fig. 6 is shown a plot of response vs range. Also, shown as a dashed line, is a theoretical response curve which assumes specular reflection. The received level is in db referred to an arbitrary reference level. This might be considered equivalent to an increase in vertical beam width and consequently a reduction in the directivity index. It was estimated that this effect would reduce the intensity of one-way transmissions by 10 db, and of echoes (2-way transmissions) by 20 db. These data help explain previous bottom-reflection data where one-way measurements with directional transducers give several db greater bottom loss than nondirectional sources. These differences were first interpreted to mean that the bottom absorption losses varied widely; they are now interpreted to mean that there was a diffusion of the energy in the directive beams, while such diffusion was not possible in nondirective sources. The method of calculation is given in Ref. 16. Schulkin and Marsh (18), analyzed a large number of reflection data at several frequencies. Figure 7, taken from that report, summarizes their data.

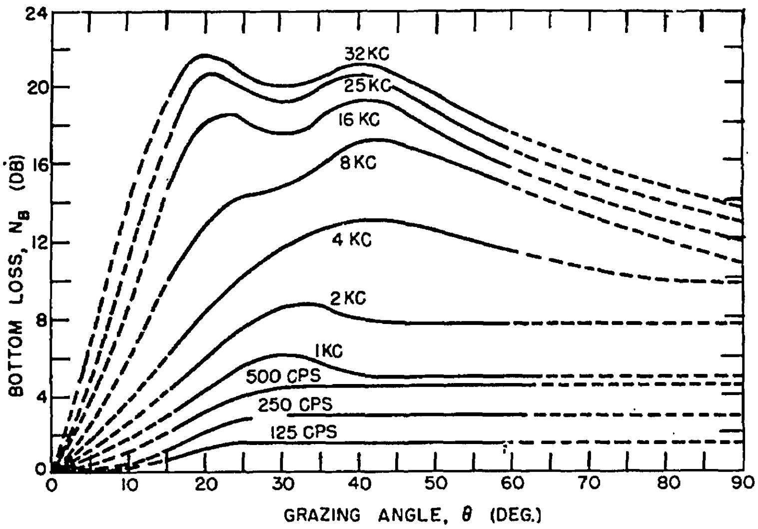

Fig. 7 - Bottom loss as a function of grazing angle

In Ref. 19 are reported one-way transmissions via the bottom between 18 miles and 28.5 miles under the following conditions: surface temperature 82°F, temperature gradient -17°F from surface to 250 ft, water depth 2300 fathoms, submarine at periscope depth, transducer tilt zero degree, and transducer directivity index -24 db. However, no numerical values of bottom reflections were obtained.

In addition, a few data were obtained off the coast of Charleston, South Carolina. Echoes from a submarine via the bottom-reflected path were obtained at a range of 18,000 yd in water 2700 fathoms deep and an isothermal layer of 100 ft. Echoes via the bottom-reflected path were obtained on a surface ship out to 24,000 yd, in shallow water (300 to 400 fathoms deep). In this last case, it is probable that there were more than one bottom reflection and hence surface reflection and that the grazing angle was small. This being so, the bottom-reflection losses could not have been very large. Multiple reflections from the bottom in moderately shallow water constitute a potential acoustic path which could yield long detection ranges.

Skip Paths

On the convergence zone study, there are a few observations and considerable theoretical analysis of the probable occurrence of the convergence zones, according to geographical location. Some calculations of zones of acoustic convergence in the Atlantic Ocean were made and reported in Ref. 20. The report purports to determine the character of the northern Atlantic Ocean with regard to its feasibility as a medium for convergence-zone transmission of underwater sound. Utilizing the gross but adequate bilinear approximation to the actual velocity profile, convergence zones throughout the northern Atlantic have been determined. Charts are given which divide the ocean into areas where this propagation path definitely exists, where it does not exist, and where it may or may not exist. Approximately 50 percent of the northern Atlantic is available for convergence-zone transmission at all times, and approximately 75 percent is available during the winter.

The parameters involved in this calculation are the surface temperature T_0 (or velocity V_0), the water depth D_W, the minimum acoustic velocity (or the water depth at which the minimum acoustic velocity is reached), and the velocity gradients in the two layers. In addition, as "initial conditions," the angle of inclination of the sound ray is required. It turns out that at the depth D_0 at which the sound velocity is equal to V_0, the direction of the sound ray is equal to its initial inclination at the surface. Thus, at this depth the ray, whose angle of inclination at the surface was zero, could be considered to begin its ascent in the ocean. Rays with negative angles of inclination at the surface begin their ascent at depths somewhat greater than D_0. Thus in order for the rays not to be intercepted by the bottom, and for convergence to occur, the water depth D_W must be greater than depth D_0.

Assumptions were made about the way the velocity of sound varies with pressure. This is the determining factor in the velocity gradient in the lower layer. The conventional value of the velocity-depth coefficient is 0.18 ft/sec per ft depth. In this report, the value 0.16 ft/sec per ft depth was used. This number was used in order to obtain calculated range results consistent with observed convergence-zone ranges. The precise reason for the necessary departure from the numerical value of the velocity-pressure gradient alone is not obvious.

On several occasions, attempts were made to study convergence in the field. On only one of these expeditions was this the primary problem under consideration. The location for that work was north of Puerto Rico in 4000 fathoms, and in such deep water there was no question about the existence of the path. All other trips involving convergence-zone study as a subsidiary topic have not been fruitful. Some reasons for lack of success are the following:

1. extreme difficulty in locating the zone (navigational difficulty)

2. questionable power capabilities and inability to steer the beam toward the target

3. weather conditions forcing the expeditions to be curtailed.

In more recent work, difficulties (1) and (2) were eliminated largely as a result of the experiences here described.

TARGET STRENGTH

Target strength of the USS BURRFISH was measured on August 2, 1955 using the transponder method; that is, the echo level from the submarine's hull was compared with the transponder signal of a known level. In general, there was little difference in the measured values from those reported earlier. Most data points were taken at beam aspect (90 deg), and at 140 deg. The average of 140 echoes at beam aspect gave a value of 30 db. The average value of target strength at aspect 140 deg was 18 db for 70 echoes. Data were taken between the ranges 1100 yd and 3500 yd.

Other measurements on August 4 at the shorter range of 700 to 1000 yd gave similar values for target strength. As is usual, the values of target strength showed considerable fluctuation. Data points are concentrated about the 30-db value, with a few being as high as 40 db and a few as low as 20 db.

BACKGROUND INTERFERENCE

The unwanted signals against which echoes must be identified are known as interfering background, background noise, etc. Limited data on two components of the background, self-noise and reverberation, are here presented.

Self-Noise

The self-noise in the LRS 2-5 transducer was measured in terms of the voltage induced in the transducer, and it was interpreted in terms of the pressure in db/1 μbar at 1 yd from the face of the transducer. Since these measurements show that the self-noise is not isotropic, one cannot make the simplifying assumption that by reducing the observations by the directivity index, one arrives at a true indication of the background noise. Rather, the interfering noise was a function of relative bearing.

The best data were obtained on June 15, 1955, with the AT-258 mounted on the LSM-398. With engines secured, sea state zero, and the transducer rigidly attached to the carriage, the self-noise levels in a one-cycle band were as follows:

Bearing	Noise Level (Conventional)	Noise Level (Observed)
000	-38.5 db	-14.5 db
150	-28.5 db	-4.5 db

Reverberation

Combined surface and volume reverberation curves were obtained by processing tape recordings of reverberation by means of the "Digiter" described in Ref. 21. The recordings were dual-channel tapes with signal on one channel and the zero time for the transmitted pulse on the other channel. The pulse length was 300 millisec and the repetition rate three pulses per minute. The averaging process was done electronically by the Digiter, which obtained an "average value" over a 2-sec interval, by scanning each interval in a series of ten 200-millisec gates.

The Digiter obtains an integral of the voltage during a 200-millisec interval. It then skips 1800 millisec to sample the 200-millisec gate of the next 2-sec interval and continues this procedure for the entire sequence of pulses. On the second round, the Digiter zero time is displaced 200 millisec, and it then repeats the process. In ten seconds, the entire sequence of reverberation return is scanned.

The Digiter obtains a summation of the absolute values of the instantaneous signal voltage during the gate periods. This summation is stored as a charge on a condenser. At the end of the gate the condenser is discharged through a resistor down to an index voltage. This discharge time, being logarithmic, is used to gate a properly chosen frequency to a counter so that the stored count will equal the db level of the signal. A printer then scans the counter and prints the number stored in the counter.

A printer prints a suitable number, one for each 2-sec interval. Thus for a 15-min sample, 450 numbers are printed. Since the pulse duration is 20 sec, there are ten numbers per ping. An observer manually sorts out the numbers for the comparable interval for each of the 45 pings, and an average value is obtained. This is taken as the "average" for each 2-sec interval. These average values were plotted in Figs. 8, 9, and 10.

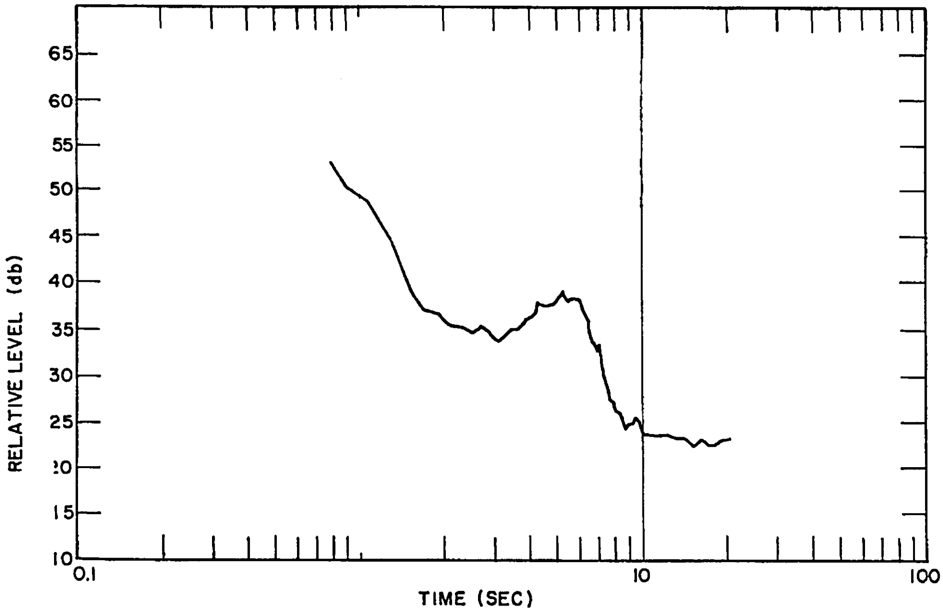

Fig. 8 - Reverberation decay at 5 kc, no duct, 2400 fathoms depth for a 300-millisec pulse length. Sea state 1.

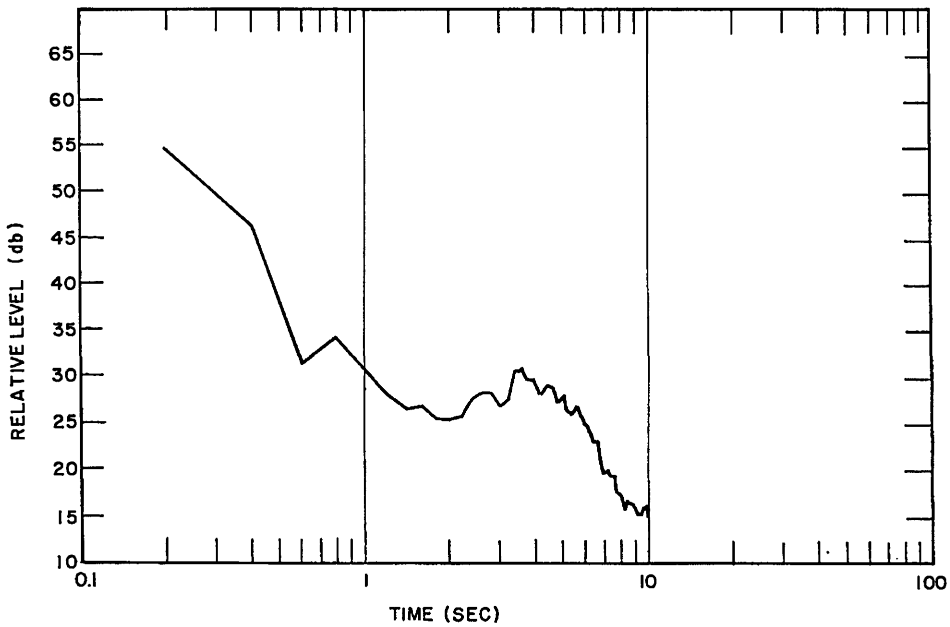

Fig. 9 - Reverberation decay at 5 kc, 40-ft duct, over 2000 fathoms depth for a 300-millisec pulse length. Sea state 1.

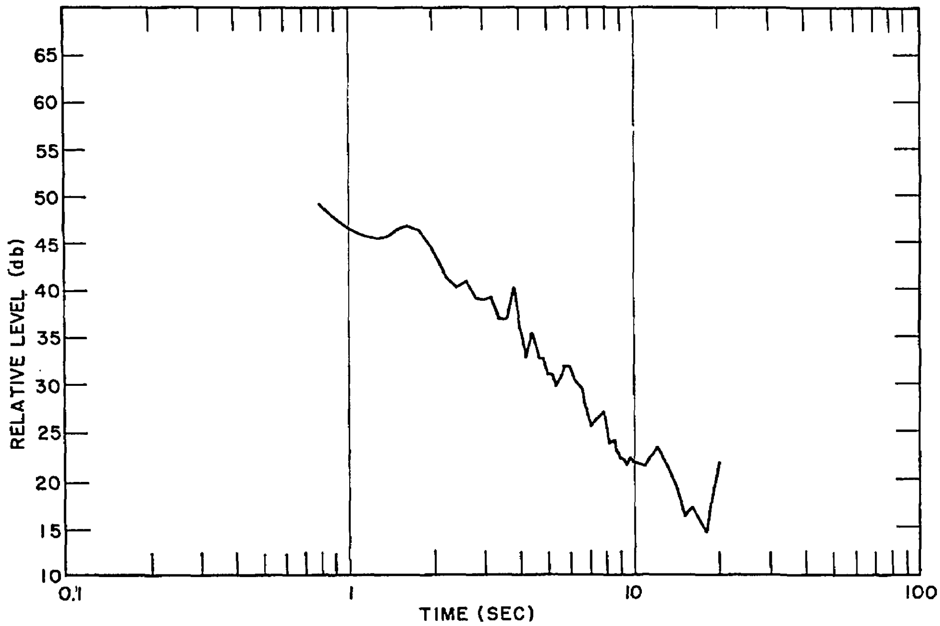

Fig. 10 - Reverberation decay at 5 kc, 80-ft duct, 1500 fathoms depth for a 300-millisec pulse length. Sea state 1.

From Figs. 8, 9, and 10, one can see that the decay rate for the combined surface and volume reverberations at 5 kc is 9 decibels per distance doubled (db/dd). This value is the same as observed at 10 kc (3). Some bottom reverberation was also in evidence. Since the transducer was at zero tilt, the bottom reverberation gives an indication of the refraction conditions.

RECOGNITION DIFFERENTIALS

An evaluation of the performance of the NB-STDS described in Chapter II was made in the laboratory. The NB-STDS ping generator was used as a signal source, and its output was added in known proportion to the Gaussian noise obtained from a random noise generator. When the occurrence of the signals was random, observers were consistently able to detect the signals when the level was 18 db below the rms level of a 1-kc band of noise. A small data sample indicates that 50-percent recognition occurs at about -20 db.

In the laboratory experiment, each pulse in the signal train had the same amplitude. It is known that significant variations in amplitude are encountered in a train of sonar echoes. The ability of the eye to recognize patterns permits an observer to detect an echo using a display of the NB-STDS type even when pulse-to-pulse fluctuations in the signal cause discontinuities or "gaps" in the pattern. A quantitative determination of the significance of this effect is difficult to obtain.

It was decided that the most directly useful measure of performance would be a detection-probability study using echoes from a submerged submarine and making direct comparison of the performance of observers using the NB-STDS with detection results obtained either simultaneously or sequentially with A-scan and aural techniques. Tests of this device were undertaken on field trips made in July and November 1955. It was planned that a number of excercises would be conducted to obtain the desired comparisons under marginal echo conditions, to determine "lost-contact" ranges for a variety of oceanographic conditions, and to evaluate the NB-STDS as an aid to classifying and tracking submerged targets. Since no controlled target could be made available on either test, quantitative data on recognition differentials could not be taken.

DETECTION OBSERVATIONS

In the course of this program, 47 detection observations were noted. Among them were a number of transponder detections, several detections of reefs, 20 of submarines, and 12 of surface ships. The detections are shown in Table 2. Only the submarine targets were controlled; the others were targets of opportunity.

Table 2
Tabulation of Detections to 20-kyd Range

Range (kyd)	Submarine	Surface Ship	All Contacts
0-5.0	6	0	6
5.1-10.0	3	5	8
10.1-15.0	5	1	6
15.1-20.0	4	1	5
Over 20	2	5	7
Total	20	12	32

The 32 observations are too few to draw conclusions as to the capabilities of the sonar in ship detection. But 7 of the 32 contacts were at ranges in excess of 20,000 yd. These are enough to show that equipment potential is not inconsistent with earlier predictions.

* * *

CHAPTER IV

RESULTS AND DISCUSSION

DETECTION ELEMENTS

As the long-range-search program advances, one can present in order of priority the important elements in obtaining long detection ranges. The factor which appears to be most important is a good acoustic path. Long detection ranges require the existence and acquisition of a suitable path, for by now it is obvious that without a path acoustic equipment is of no avail. The second element is a sonar capable of exploiting the path. The parameters which are significant in promoting the efficiency of a sonar in a path have been discussed earlier in the report. The third element is the sonar vehicle and platform. Once a path is located and a suitable sonar is available to exploit that path, then a suitable vehicle and platform are required to transport the sonar to the locations of good acoustic paths. The vehicle also must be able to operate efficiently at the desired or necessary speeds and to provide a reliable and efficient platform for sonar operation.

The program showed that the means of conveying the sonar to the acoustic path can be a serious problem. The vehicle and platform are not to be taken for granted, but must be worked out for each case. The necessary analysis and engineering are integral parts of the sonar problem, and distinct from the acoustic and oceanographic aspects. The LRS 2-5 program involved a major study in sonar vehicle and platform, since these were the limiting factors in the performance of the LRS 2-5 system.

DETECTION EQUIPMENT

Where a good surface channel exists, presently developed detection equipment is adequate, provided a suitable choice of power and frequency is made for the sonar. That combination can be arranged in a convenient equipment at 10 kc. Significant increases in range were not obtained at 5 kc with the LRS 2-5 over 10 kc with the LRS 1-10; this leads to the conclusion that the LRS 1-10 is adequate for duct operations. The choice of 10 kc is not intended to be indicative that 10 kc is the optimum frequency, but only that for surface-bounded ducts the LRS 1-10 sonar is a good system. For paths other than surface-bounded ducts, other frequencies might be better.

The 5-kc experience indicated that when an acoustic path existed, and when the transducer was placed in this acoustic path, fairly long detection ranges (20 to 25 kyd) could be obtained with the LRS 2-5 sonar. This conclusion is borne out by the tabulation of detection observations (see Table 2). The prediction of the occurrence of paths is then of prime importance. This occurrence may be presented as a probability with the two parameters geographic location and time of the year.

TOWING GEAR

The handling gear caused no substantial delays; the preliminary engineering and the shakedown tests provided the means to design and procure adequate and reliable auxiliaries. The last element to yield to laboratory development and design was the cable. The advances in designing a satisfactory tow cable have now reached the point where it is possible to make a cable capable of towing the 1-kc transducer without being subject to vibrational failures.

The towed system was employed as the platform for many reasons. The towed sonar equipment of the LRS 2-5 system was designed primarily as a convenient and economical means of placing the transducer in the water. The transducer and the mechanism associated with it for training and tilting were of such a size that a conventional hull-mounted installation was precluded primarily because of dry-docking difficulties. The size of the towed body in the same way made installation on a destroyer-type ship out of the question; this resulted in the choice of an LSM as the vehicle. On such a ship there was no problem of space availability and weight and movement compensation. Further, choice in sonar depth can be an advantage, and a towed system, when successful, can provide the means to obtain this flexibility (3). With the improvements in cable design and construction which are being pursued in connection with the LRS 3-1 program, the advantages of a towed, surface ship sonar may be tested and realized.

* * *

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions are drawn as a consequence of the research so far described.

- Both in research in underwater acoustics and in operational performance, consideration must be given to the entire ensemble of sonar, vehicle, and platform.

- There are three necessary elements in sonar detection: the existence of an acoustic path, a sonar system to exploit the path, and a reliable vehicle to transport the sonar to the path. The third factor is at least as important as the first two and has been largely overlooked or taken for granted in the past.

- Sonar design is sufficiently far advanced to permit us to build and use efficiently very large transducers.

- The sonar equipment (consisting of the transducer and its associated electronics) is not the limiting factor in sonar detection. The vehicle and the medium are the limiting factors.

- Where a good channel exists, presently developed detection equipment is adequate to detect targets in that duct out to 25 kyd.

RECOMMENDATIONS

It is therefore recommended that:

- Research be conducted on the most suitable combination of vehicle and platform for reliable delivery of the sonar equipment to the various acoustic paths.

- Research on towing and cable design be conducted. This research should be conducted as a project in itself, and not as a part of a sonar project.

- Oceanographic research be conducted on the existence and probability of occurrence of acoustic paths in addition to the four listed in Chapter I.

* * *

APPENDIX A

DETAILED PRELIMINARY ANALYSIS

DISTINGUISHING PARAMETER

In Ref. 3,* it was found convenient to use the expression E_1 as a significant characteristic of a sonar system. E (without subscript) was defined as the excess in decibels of the echo level over the level required for 50-percent probability of detection. The quantity E_1 is defined as the hypothetical echo excess at a target range of 1 yd. The two terms are related by the equation

$$E = E_1 - \text{losses}. \tag{A1}$$

At the range at which the losses equal E_1, E vanishes. At that range, there is a 50-percent probability of detection.

The delineation of E_1 is contained in the following equation.

$$E_1 = (I_1 + T) - (N - \Delta + \delta) \tag{A2}$$

where

I_1 = intensity at 1 yd from the source

T = target strength

N = omnidirectional noise in a one-cycle band

Δ = directivity index at reception

δ = recognition differential, i.e., the ratio of signal to noise in a one-cycle band out of the transducer for 50-percent probability of detection.

The value of E_1 as a characteristic function lies in the fact that it takes into account the radiation capabilities of the equipment (I_1 and Δ), the conditions under which it will be used (T and N), and the effectiveness of the signal-processing auxiliaries (δ).

ACOUSTIC PATHS

Four paths, described in Ref. 3, are as follows:

1. The surface-bounded duct
2. The reflection via the bottom
3. The skip path
4. The submerged duct.

*The same terminology and symbols used in the "Preliminary Analysis" of Ref. 3 will be employed here.

In the LRS 1-10 program, the surface-bounded duct was frequently found and used extensively. A few echoes were obtained by means of the bottom-reflected path. None was observed in the last two categories, except shallow submerged ducts, as produced by the afternoon effect.

In the LRS 2-5 program, attention was focused on the first three paths. When submerged ducts are deeper than 150 ft, they cannot be used, since the depth of submergence of the transducer is limited to that depth. This consequently limits observation to shallow submerged ducts.

EQUIPMENT CHARACTERISTICS AND PERFORMANCE

With the above considerations in mind, the effectiveness of the 5-kc equipment was envisaged in terms of E_1 and the paths which would be exploited. On the basis of experience gained with the LRS 1-10, confidence was felt that a system could be designed and built with increased power, increased transducer size, and improved signal-processing devices. It was thought that a system with an E_1 of 192 db could be built, although in the very early plans an E_1 of 205 db was anticipated.

RANGE ESTIMATES

To estimate the ranges which this equipment would yield, the acoustic paths and loss coefficients at 5 kc related to these paths need to be estimated. The absorption α_0, obtained from Ref. 14, is equal to 0.1 db/kyd at 70°F. The leakage coefficient α_L, obtained from Ref. 15, is equal to 0.8 db/kyd. The loss at bottom reflection cannot now be estimated quantitatively, but past experience indicates that the reflection coefficient is a function of frequency and grazing angle. The best that can be said at this time is that the bottom-reflection losses at 5 kc should be less than at 10 kc.

The round-trip losses in channels were given in Ref. 3 by the equation

$$2L = 40 \log (1000) + 20 \log R + 2(\alpha_0 + \alpha_L)R, \tag{A3}$$

where R is the range in kiloyards and L is the one-way transmission loss. Assuming $2L = 192$ db $= E_1$, a range of 25 kyds should be obtained in good surface channels. In bottom-reflected paths, it is estimated that better ranges than at 10 kc should be obtained.

The losses at skip paths of 35 miles are given empirically by

$$2L = 33 \log 1000 + 33 \log (70N) + 2\alpha_0 (70N), \tag{A4}$$

where N = 1, 2, 3, ..., the number of skip zones. When conditions are as good as this, reception from the first skip zone should be possible.

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